Technical Barriers to the Consumption of Higher Blends of Ethanol

Stephanie Searle, Francisco Posada Sanchez, Chris Malins & John German
The International Council on Clean Transportation

February 2014

THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

DISCLAIMER

The International Council on Clean Transportation (ICCT) prepared this paper at the request of the Bipartisan Policy Center (BPC). BPC is releasing this paper as it was presented to us. The findings and opinions expressed in this paper are solely those of the authors. BPC takes no position on the findings nor conclusions developed in this paper, and this paper does not necessarily represent the views of the Bipartisan Policy Center, BPC staff, its founders, its board of directors, or the RFS advisory group.

ABOUT BPC

Founded in 2007 by former Senate Majority Leaders Howard Baker, Tom Daschle, Bob Dole and George Mitchell, the Bipartisan Policy Center is a non-profit organization that drives principled solutions through rigorous analysis, reasoned negotiation and respectful dialogue. With projects in multiple issue areas, BPC combines politically balanced policymaking with strong, proactive advocacy and outreach.

ACKNOWLEDGEMENTS

Thanks to the Bipartisan Policy Center for funding this work, and to Nic Lutsey and Oscar Delgado at the International Council on Clean Transportation, and to Adam Christensen at Johns Hopkins University for reviewing this paper and providing information.

Substantial changes in energy markets, persistent challenges in courts, and difficulties in the implementation of relevant enacting laws have kept the Renewable Fuel Standard (RFS) at the forefront of energy policy discussions. There are both strong advocates in support of holding firm on the existing requirements and calls for outright repeal. But there also exists an active middle ground focusing on reforming, not repealing, the RFS.

The Bipartisan Policy Center (BPC) is undertaking a yearlong effort aimed at fostering constructive dialogue and action on reforming the RFS. To do this, BPC is convening a diverse RFS advisory group to discuss opportunities for reform, hosting public workshops to solicit broad input, and ultimately publishing viable policy options based, in part, on the advisory group's deliberations.

As part of this effort, BPC has commissioned a series of background papers on various RFS topics. These papers are targeted at a broad audience that includes not only BPC's advisory group, but also policymakers, industry, and the public, with the intention of educating and informing the wider debate surrounding this issue. Given a topic as complex as the RFS, these papers cover multiple issues, providing a focused view from the perspectives of technology, infrastructure, policy, and law. The first three background papers listed will be released in early February. The remaining two, which are two separate law firms' perspectives on the same topic, will be released by the end of February.

1. **Technical Barriers to the Consumption of Higher Blends of Ethanol**
   The International Council on Clean Transportation

2. **Petroleum and Renewable Fuels Supply Chain**
   Stillwater Associates LLC

3. **Inventory of Federal Regulations Affecting Biofuels other than the Renewable Fuel Standard**
   Van Ness Feldman

4. **The Environmental Protection Agency's Authority to Amend the Renewable Fuel Standard**
   Sutherland Asbill & Brennan LLP

5. **The Environmental Protection Agency's Authority to Amend the Renewable Fuel Standard**
   Bracewell & Giuliani LLP

BPC is releasing these papers as they were presented to us. The findings and opinions expressed in these background papers are solely those of the author(s). BPC takes no position on the findings nor conclusions developed in these papers, and they do not necessarily represent the views of BPC staff or the RFS advisory group.

To read other background papers in the series or for additional information about this effort, please visit http://bipartisanpolicy.org/projects/energy/renewable-fuel.

Table of Contents

Executive Summary

The U.S. Renewable Fuel Standard (RFS) mandates the consumption of biofuel in road transport fuel. The first RFS program (RFS1) required biofuel to be blended into gasoline over the period of 2006 to 2012. In 2007, the RFS1 was amended and extended to 2022, becoming the RFS2. To date, most of the RFS2 biofuel mandate has been fulfilled with ethanol, which is now typically blended into gasoline at a 10 percent mixture by volume (E10). Given stagnating demand for gasoline due to rising fuel economy in the nation's fleet and other factors, further increases to U.S. ethanol consumption would require the use of higher blends of ethanol, either in "normal" vehicles or in flex-fuel vehicles (FFVs) designed to tolerate blends of up to 85 percent ethanol (E85).

This study reviews technical barriers to the consumption of blends of ethanol above 10 percent. This includes the effect of higher ethanol blends on passenger vehicles and smaller engines, as well as the impact on infrastructure such as pipelines, storage tanks, and fuel dispensers. Note that we do not present a comprehensive review of all of the barriers to uptake of higher ethanol blends. For instance, most car warranties do not cover the use of blends above E10. In addition, higher ethanol blends and related equipment may cost more than E10, and corn ethanol has been criticized by some experts and stakeholders for increasing food prices and for having negative impacts on the environment. This study does not consider these areas and instead focuses only on *technology issues* that must be addressed for the consumption of higher blends of ethanol.

Vehicle Compatibility

The primary technical concerns with using intermediate blends of ethanol in vehicles include: reduced fuel economy due to the lower energy density of ethanol; increased emissions of pollutants such as nitrogen oxides (NO_x) due to higher catalyst temperatures; corrosion of metals and other materials in engines and fuel systems; degradation of elastomers, polymers, and seals, which can lead to fuel leaks; and phase separation of water and ethanol from gasoline.

Given that the energy density of ethanol (the amount of energy in one gallon of fuel) is about one-third lower than the energy density of gasoline, cars drive fewer miles per gallon (mpg) when operating on ethanol blends compared with unblended gasoline. As such, existing cars driving on higher blends of ethanol will experience range reduction for a given fuel tank size. Fuel tanks could be made larger in new vehicles to partially address this problem, but there is no way to directly offset the lower energy density of ethanol compared with gasoline.

There are theoretical reasons to be concerned that cars operating on higher ethanol blends than they were designed for could emit greater concentrations of pollutants in their exhaust gas. Cars need oxygen from air to combust gasoline, and under normal operation this ratio of air/fuel is carefully controlled so that the fuel burns optimally. If the ratio is not adjusted when using ethanol blends, the exhaust temperature will rise and, over time, can result in deterioration of the catalytic converter. This situation can increase the level of certain pollutants in the vehicle's exhaust. Modern cars have the ability to prevent this imbalance by automatically adjusting the air/fuel ratio depending on the ethanol content of the fuel. Older vehicles, however, as well as many motorcycles, lawn mowers, and other off-road equipment, do not have a mechanism for automatically adjusting the air/fuel ratio, which can pose a problem as described in more detail below.

Ethanol blends are associated with higher emissions of the toxic substances formaldehyde and acetaldehyde, but their combustion produces lower levels of benzene and the carcinogen 1,3-butadiene. These blends can also be expected to result in lower emissions of particulate matter (PM), although PM emissions from gasoline vehicles are already extremely low.

There are also concerns that higher blends of ethanol could increase evaporative emissions, or emissions of evaporated, unburned fuel, because ethanol blends have a higher vapor pressure than gasoline at low to mid concentrations. However, given that E10 has the highest vapor pressure of any blend level, it is not expected that increasing the ethanol content of fuel above E10 will result in higher evaporative emissions.

Claims that E15 cannot be safely used in newer (2001 and later) vehicles focus primarily around a set of studies by the Coordinating Research Council (CRC). Although the CRC reported leaks and other problems in some vehicle tests, overall most other studies have found that E15–E30 causes only slight damage to vehicle components. There is little evidence that these low-intermediate ethanol blends damage metals, and E15 does not appear to affect plastics, polymers, and similar materials differently than E10. Taking all of these studies together, we conclude that vehicles model year 2001 or later can safely consume E15, provided warranty issues can be managed. Although there is some evidence showing vehicles older than 2001 can tolerate ethanol blends up to E30, these vehicles do not have the same technological advantages as newer cars, and it is likely not prudent to use higher ethanol blends in them, even ignoring warranty issues. FFVs that can operate on E0–E85 are currently being produced at high volume (17 percent of all U.S. car sales in 2011), and non-FFV vehicles can be retrofitted at moderate cost.

Finally, given that ethanol readily mixes with both gasoline and water, water can become incorporated in the fuel blend. If water contamination is high enough, the ethanol/water mix will separate from the gasoline and form a layer at the bottom of the tank, in a process known as phase separation. In general, it is not expected that water contamination with ethanol blends will be high enough to cause problems with vehicle operation. The risk of phase separation can be reduced by the addition of solubility improvers.

Small Engines and Off-road Applications

Equipment with small gasoline engines, such as lawnmowers, snowmobiles, and small boats, have more serious compatibility issues with higher ethanol blends. New equipment of these types can be designed to operate on higher ethanol blends, but retrofitting existing equipment is not likely to be practical. The possibility of replacing lead additives with ethanol in aviation gasoline for small aircraft should be studied further. Large aircraft and ships use different types of fuel, and while some types of biofuel can be blended into aviation fuel, ethanol cannot be used in these applications.

Infrastructure

Fueling infrastructure may have material incompatibility with ethanol, especially with regard to elastomers.[1] Still, there is evidence that E15 may be safely used with some existing fuel dispensers and pipelines that have been delivering E0 or E10, provided they are cleaned of all fuel and residual fluids before higher ethanol blends are introduced. Technology is available for the production of new dispensers, storage tanks, and pipelines that can accommodate ethanol blends E15–E85, and many existing infrastructure elements can be retrofitted for this purpose. At the same time, stations offering higher ethanol blends will still need to offer E0 or E10 for older vehicles and small engines, and a system to minimize the risk of misfueling must be developed.

Timeline for Consumption of Higher Blends of Ethanol

This review also considers the amount of time needed to make necessary technological changes to vehicles and infrastructure in order to consume higher blends of ethanol. These timelines, in addition to solutions for the potential problems discussed above, are summarized in Table 1.

Table 1. Summary of technical barriers to using higher blends of ethanol, potential solutions to those barriers, and timeframe necessary for technical solutions. This timeline does not consider non-technical barriers.

Equipment	Problem	Solution for use of E10-E20	Solution for use of E25-E85	Timeframe for resolving technical barriers only,[2] for E15-E20 use	Timeframe for resolving technical barriers only,[3] for E25-E85 use
Vehicles	Reduced range from fuel economy loss	No solution	No solution		
	Increased temperatures and pollutants in exhaust	Avoid fueling older vehicles with E15-E20; post-2000 vehicles likely compatible	Increase production of new FFVs; retrofit other vehicles	No time needed	About 5 years
	Material incompatibility and leaks	Avoid fueling older vehicles with E15-E20; post-2001 vehicles likely compatible	Increase production of new FFVs; retrofit other vehicles	No time needed	About 5 years
	Phase separation	No problems likely	No problems likely; Can add solubility improvers to fuel	No time needed	No time needed
Motorcycles, boats, and small engines	Increased temperatures and pollutants in exhaust; material incompatibility	New vehicles and machines can be designed for E15-20; existing vehicles and machines should not use higher ethanol blends	Not clear there is a practical solution	Several years for machine turnover	Not advised to fuel these vehicles and machines on ethanol in near-term
Fuel dispensers	Material incompatibility	Some newer dispensers can use E15; retrofit others; development of a system to minimize risk of misfueling	Retrofit or replace dispensers	No time for some existing dispensers; hours to days for retrofits; 1-2 years for misfueling system	Hours to days for retrofits; 1-2 years for misfueling system
Fuel storage tanks	Material incompatibility	Retrofit and clean tank	Retrofit or replace	Days	Days to months
Pipelines	Corrosion of steel and other material incompatibility	Possibly no modifications needed for E15; for E20, add inhibitors	Add liners to inside of pipeline and inhibitors to fuel; build new pipelines	No time to several days	Months to 3 years
	Water contamination	Clean pipeline and check seals	Clean pipeline and check seals	Days	Days

Finally, we present two hypothetical scenarios of the future consumption of higher blends of ethanol (ignoring non-technical challenges), in which:

1. E15 increases to 100 percent of gasoline consumed in 2022 (the "E15 in 2022" scenario); or

2. E85 rises to 25 percent of all gasoline consumed in 2022, and the remaining 75 percent of consumption becomes E15 by 2022 (the "25 percent E85 in 2022" scenario).

These two consumption scenarios are then evaluated with regards to how they may or may not satisfy two projections of RFS2 mandated volumes: revised and original. The analysis finds that if the cellulosic volumes in the RFS2 continue to be revised downward (the "revised" mandate), the RFS2 could be approximately met from 2016–2022 through the "E15 in 2022" scenario, and could be fully met (and in fact exceeded) from 2015–2022 given consumption in the "25 percent E85 in 2022" scenario. The RFS2 mandate as originally set in the statute (the "original" mandate), which calls for 36 billion gallons of biofuel to be consumed in 2022, could be satisfied from 2017–2022 by the levels in the "25 percent E85 in 2022" scenario, but not at any time by the "E15 in 2022" scenario. As a comparison with these scenarios and mandated levels, we also present a "repealed" projection where E10 consumption remains constant (in proportion to overall gasoline demand) through 2022.

It is important to note that significant other barriers exist to the uptake of higher ethanol blends, and the analysis here does not demonstrate whether these scenarios of ethanol consumption are realistically achievable. Current trends of rollout of ethanol-compatible vehicles and infrastructure have been much slower.

Overall, this study finds that technical barriers do not stand in the way of implementation of the RFS2 to 2022. At the same time, we did not consider the future production potential for ethanol or a myriad of other issues such as cost, politics, and negative impacts on food prices and the environment.

Introduction

U.S. federal and state policies, regulations, and incentives have promoted the use of ethanol in road fuel for decades. The current phase of ethanol support began with the Reformulated Gasoline (RFG) program mandated in 1990, which required a certain oxygen content in gasoline to reduce pollution in vehicle exhaust.[4] At first, this requirement was largely met by blending gasoline with methyl tertiary butyl ether (MTBE). Following cases of groundwater contamination by MTBE in the early 2000s, ethanol has become the primary oxygenate for U.S. gasoline. Then, the Energy Policy Act of 2005 (EPACT05) created the Renewable Fuel Standard (RFS). The first phase of the RFS, now referred to as RFS1, mandated 4 billion gallons of renewable fuel to be blended into gasoline in 2006, and 7.5 billion gallons (or about 6 percent of gasoline by volume) in 2012. The RFS1 was amended and extended in 2007 with the Energy Independence and Security Act (EISA), becoming the RFS2. The RFS2 split biofuel into four categories, defined by feedstock and by the required greenhouse gas reduction compared with gasoline or diesel, and mandated volumes in all categories increase over the duration of the RFS2 (2010–2022).

To date, the majority of biofuel used for compliance with the RFS2 has been ethanol produced from corn and (to a lesser extent) Brazilian sugarcane. In 2013, the RFS2 mandated the consumption of 16.55 billion gallons of renewable fuel in total; this requires blending approximately 9.6 percent biofuel (mostly ethanol) in road fuel.[5] Some U.S. states mandate higher blending of ethanol than would be required to comply with RFS2; for example, all gasoline sold in Minnesota is required to be E20 starting in 2015.[6,7] Before 2010, 10 percent ethanol in gasoline (E10) was set as the limit by the Environment Protection Agency (EPA) for the maximum blend of ethanol that could be used in unmodified road vehicles without risking compromising operation and performance. EPA has since issued waivers to allow the use of 15 percent ethanol in gasoline (E15) in vehicle models introduced in 2001 and later, based on tests showing E15 does not damage these vehicles.[8,9] However, this ruling has faced opposition from the oil and automotive industries, among other stakeholders, due to concerns that E15 could damage vehicle engines and other components.[10,11] Furthermore, granting a waiver for E15 does not address the need to provide a dual-stream refueling infrastructure, with E15 for newer vehicles and E10 or straight gasoline (E0) for older vehicles and small engines.

This study aims to identify the technical barriers to using ethanol blends above E10 and possible solutions to those barriers. It provides a broad overview of the risk of damage from using E15 and higher ethanol blends in cars, in other vehicles and non-road equipment running on smaller gasoline engines, as well as in fueling infrastructure such as pipelines, storage tanks, and gasoline dispensers. It identifies the technical changes that would be required in each of these areas to safely use ethanol blends of 15–85 percent. Lastly, it discusses the amount of time needed to make necessary technological changes to vehicles and infrastructure in order to consume higher blends of ethanol and compares this timeline with projections of RFS2 implementation.

Vehicle Compatibility

Before approving the use of E15 in newer vehicle models, EPA worked with the U.S. Department of Energy (DOE)[12] to test the effects of E15 on vehicle components.[13] A number of studies on the effects of E15–E30 have also been published by other parties. The primary technical concerns with using intermediate blends of ethanol in vehicles include:

- reduced fuel economy due to the lower energy density of ethanol;
- increased emissions of pollutants such as NO_x due to higher catalyst temperatures;
- corrosion of metals and other materials in engines and fuel systems;
- degradation of elastomers, polymers, and seals, which can lead to fuel leaks; and
- phase separation of water and ethanol from gasoline.

Fuel Economy With Ethanol Blends

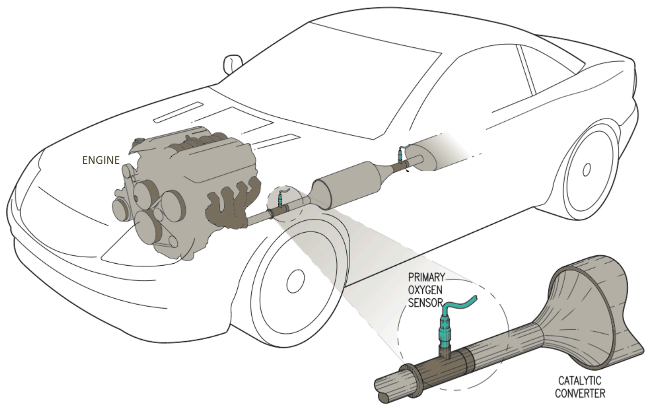
Cars drive fewer miles per gallon (mpg) when operating on ethanol blends compared with unblended gasoline. This is expected because ethanol has about one-third lower energy density (amount of energy in one gallon of fuel) than gasoline. Studies have generally found that the fuel economy loss with ethanol blends is consistent with their lower energy density—that is to say, cars will drive the same distance per unit of energy when running on gasoline or ethanol blends.[14,15,16] Existing cars driving on higher blends of ethanol would thus experience range reduction for a given fuel tank size. Fuel tanks could be made larger in new vehicles to partially address this problem with higher ethanol blends,[17] but there is no way to directly offset the lower energy density of ethanol compared with gasoline. Tailpipe emissions of carbon dioxide (CO_2) from the combustion of ethanol and gasoline are similar on an energy basis, and so using ethanol does not affect a vehicle's tailpipe CO_2 emissions per mile driven. EPA has investigated the potential that cars running on E30 could be more efficient on an energy basis if their engines are designed for that fuel mix.[18,19] However, such vehicles would not achieve these efficiency gains if designed for E30 and fueled with lower ethanol blends. They would also experience reduced performance or possibly detonation, a problem caused when the fuel mixture combusts prematurely; this can damage engines.

Effects of Ethanol on Car Emissions

There are theoretical reasons to be concerned that cars operating on higher ethanol blends than they were designed for could emit greater concentrations of pollutants in their exhaust gas. Cars need oxygen from air to combust gasoline, and under normal operation, this ratio of air/fuel is carefully controlled so that the fuel burns optimally. In the cylinder where combustion takes place, the fuel evaporates before it is burned, and this evaporation helps cool off the air/fuel mixture and exhaust gas. Ethanol contains oxygen in its molecular structure (while gasoline does not), and so requires less air for combustion per unit fuel; in other words, the optimal air/fuel ratio for ethanol blends is lower than for pure gasoline. If the same air/fuel ratio for gasoline is used for ethanol blends, there will be too much air for the amount of fuel in the cylinder—this is called "enleanment."[20] In this situation, there is not enough fuel evaporation to cool the mixture, and the temperature of the exhaust gas rises.[21] This raises temperatures inside the catalytic converter,[22] and over time, this can accelerate catalyst deterioration. In addition, excess oxygen in the exhaust can inhibit proper functioning of the catalytic converter, which converts NO_x into stable nitrogen and oxygen gases. To summarize, enleanment from using high-oxygen fuels like ethanol can theoretically lead to overheating of the catalytic converter and to increased emissions of harmful pollutants.

Modern cars have the ability to prevent enleanment by adjusting the air/fuel ratio depending on the ethanol content of the fuel. There is an oxygen sensor on the exhaust line in between the engine and the catalytic converter (Figure 1). If the sensor detects elevated oxygen in the exhaust, indicating enleanment, it sends a signal to the fuel injector to decrease the air/fuel ratio. This keeps the catalytic converter operating at the right air/fuel conditions. Vehicle systems with an oxygen sensor are referred to as "closed loop," whereas those without control over the air/fuel ratio are referred to as "open loop" systems. Since 2001, U.S. cars have been equipped with more accurate oxygen sensors capable of correcting the air/fuel mixture relatively quickly, while in older cars (1981–2000),[23] simpler oxygen sensors take a longer time to adjust.[24] All cars made in 1981 and after have closed loop systems.[25] Modern vehicles will still always operate under open loop conditions when in full throttle or during a cold start.[26] Older vehicles, as well as many motorcycles, lawn mowers, and other off-road equipment, are open loop and do not have a mechanism for automatically adjusting the air/fuel ratio; this is discussed in more detail in the sections below on small engines and non-road vehicles.

Figure 1. Diagram of vehicle components, showing placement of engine, oxygen sensor, and catalytic converter. Image by the International Council on Clean Transportation.



Some studies have measured temperature increases in the exhaust gas and catalytic converters of cars, both pre-2001 and post-2001, operating on E15 or E20 when under open loop conditions (i.e., without feedback from the oxygen sensor), compared with emissions when operating on pure gasoline.[27,28,29] The studies found slightly higher emissions of NO_x and lower emissions of carbon monoxide (CO) and unburned hydrocarbons in vehicles operating on E15 or E20 compared with those using E0.[30,31] One study showed that under closed loop (normal) conditions, the exhaust temperature did not increase with higher ethanol blends;[32] this is as expected given that the oxygen sensor adjusts the amount of fuel delivered to maintain the same air/fuel ratio in closed loop operation. In a highly publicized study by the Coordinating Research Council (CRC),[33,34] out of seven vehicles tested,[35] one failed emission standards on E15, but a duplicate vehicle passed on E15 and both passed using E20. In an Australian study, one vehicle produced higher NO_x emissions at high mileage on E20 compared with E0, and this was attributed to higher catalyst temperatures over time.[36] Interestingly, another study reported no change in emissions with vehicles model year 1985–1998 when operating on E30 under closed loop conditions, although this study did note these older cars required a half-hour of driving before the fuel injector fully adjusted to the ethanol content of the fuel, which may be expected with the first-generation oxygen sensors used in this vehicle age class.[37] Older vehicles (pre-1980s) that have no air/fuel control may be incompatible with even E5.[38]

Ethanol blends are associated with higher emissions of the toxic substances formaldehyde and acetaldehyde,[39,40,41,42] but they produce lower levels of benzene and the carcinogen 1,3-butadiene. Using California's relative toxicity factors, one study calculated that the overall toxicity of emissions from ethanol blends was lower than for gasoline.[43] All ethanol blends can also be expected to result in lower concentrations of PM in the exhaust gas than gasoline,[44] and PM is associated with lung and heart disease.[45] On the other hand, PM emissions from gasoline vehicles are already extremely low.

There are also concerns that higher blends of ethanol could increase evaporative emissions, or emissions of evaporated, unburned fuel from the fuel tank and from joints and seals along the fuel line, because ethanol blends have a higher vapor pressure than gasoline at low to mid concentrations. For example, the CRC reported higher evaporative emissions in fuel systems with 5.7 percent ethanol compared with pure gasoline.[46] However, E10 has the highest vapor pressure of any blend level; vapor pressure decreases with ethanol content thereafter. E15 and E20 have slightly lower vapor pressure than E10, and E85 has a vapor pressure significantly lower than E10 or gasoline.[47,48,49] Thus, it is not expected that increasing the ethanol content of fuel above E10 will result in higher evaporative emissions.

Ethanol Effects on Materials and Fuel Leaks

Ethanol is more corrosive than gasoline because it contains more dissolved oxygen, and this has led to concerns that ethanol blends above E10 could damage materials in car engines and fuel systems. Ethanol damage to materials could potentially lead to leaks or fuel filter blockage, especially in older vehicles.[50] Partly for these reasons, most car warranties in the United States only cover usage of E0–E10.[51]

Metals used in engines and other vehicle parts have generally not been found to be susceptible to corrosion by low to mid blends of ethanol. In a review of the literature, the National Renewable Energy Laboratory (NREL)[52] reported slight and insignificant corrosion of vehicle metals with E10 and E20, even when testing with an "aggressive" ethanol blend representing the "worst case" contaminated fuel that could potentially be found on the market. The Australian study mentioned above found slightly greater wear on some metallic engine components in a few vehicles operating on E20 vs. E0, with no effect on performance.[53] Other studies on legacy vehicles found no effect of E15,[54,55] E20,[56] or E30[57] on engine materials or other metal parts.

Ethanol may also affect elastomeric components (elastic polymers, or rubber- and plastic-like materials) in vehicles by changing their dimensions and by reacting with the material.[58] However, an NREL review found that elastomer properties changed when exposed to E10 versus E0, but that there was no difference in properties when comparing E15 with E10.[59] As with metals, studies on legacy vehicles (model years 1994–2001) did not observe any degradation of elastomers, polymers, or any other materials with E15[60,61] or E20.[62]

While the CRC study on engine durability[63] did not specifically measure changes in materials with exposure to ethanol, it did report leakage from engines in two vehicles operating on "aggressive" E15, and four out of seven vehicles at "aggressive" E20, leading to engine failure in two (although duplicates of some of these vehicles passed). These results were downplayed in a review by NREL[64] because of the small sample size and statistically insignificant results. Indeed, the CRC study reads, "[S]ince this study was designed for scoping purposes, the findings should only be used to identify where additional testing should be performed" (p. 12).

NREL also criticized CRC's use of the leakdown test,[65] because there is no agreed threshold. However, the leakdown test is very robust, and we do not consider this criticism to be valid. It would be similar to claiming the SAT is not a useful test because there is no particular score that indicates failure. The CRC study also identified problem areas in various components of the fuel system (fuel pump seals, filler hoses, fuel level senders, and valves). On the other hand, the CRC did not find any negative impacts from soaking fuel pumps in "aggressive" E20,[66] and other studies have reported no leaks in legacy vehicles operating on E15,[67,68] E20,[69] or E30 in vehicles model years 1985–1999.[70] In addition, a study at the University of Minnesota reported no problems caused by ethanol when a large number of vehicles were driven on E20 under normal conditions, although it should be noted this study did not test for deterioration under high-mileage or stressful conditions.[71] Apart from the small sample size, it is not clear why leakage was observed in the CRC study but not in the others cited here.

Although the CRC reported leaks in some vehicle tests, overall most studies have found that E15–E30 causes only slight damage to vehicle components. There is little evidence that these low-intermediate ethanol blends damage metals, and E15 does not appear to affect plastics, polymers, and similar materials differently than E10.

Phase Separation of Water and Ethanol from Gasoline

Gasoline typically contains small amounts of water contamination, but since gasoline and water don't mix with each other, the water stays at the bottom of the fuel tank. Ethanol, on the other hand, readily mixes with both gasoline and water, and allows water to become incorporated in the fuel blend. If water contamination is high enough, the ethanol/water mix will separate from the gasoline, forming a layer at the bottom of the tank—this is "phase separation."[72] The fuel line is at the bottom of the tank, and so a high concentration of water/ethanol may be drawn out and cause problems starting the car.[73] However, phase separation only occurs at relatively high concentrations of water[74,75,76] and generally is not a major concern. The risk of phase separation can be reduced by the addition of solubility improvers.[77]

Flex-Fuel Vehicles (FFVs)

FFVs are designed to be able to run on pure gasoline or on ethanol blends up to E85.[78] FFVs are popular in Brazil, and their market share in the United States has grown in recent years. Given that it's just as easy to make FFVs that can operate on all blends of ethanol up to E85 as to engineer vehicles that have an ethanol limit greater than E20 but less than E85, we do not consider the latter category here.

FFVs are not much different from regular cars, and it’s relatively easy and inexpensive to produce an FFV instead of a regular car. Several relatively minor technical adjustments are required, including replacing or coating certain metal and elastomeric components, increasing the fuel system capacity to account for the lower energy density of ethanol, and installing a sensor in the fuel line that measures alcohol concentration.[79] FFVs can run on pure gasoline or any blend of ethanol up to E85 and generally operate the same as conventional vehicles. Non-FFVs can also be retrofitted to become flex-fuel and retrofit kits are available, although such conversions may be expensive for the consumer and care must be taken to ensure the converted vehicle still meets emission regulations.[80] In addition, FFV conversions must be done by a certified technician, or the owner may lose the vehicle warranty.

The main downside to FFVs is the cost; new FFVs cost $70–100 more to manufacture than a non-FFV of the same vehicle model.[81,82] While this additional cost is small compared with the purchase price of a new vehicle, it adds up for the manufacturer when considering all vehicles produced in a year. In addition, changes must be made to the assembly line, which presents an upfront cost. Through 2016, automakers receive additional credits from selling FFVs to comply with EPA’s greenhouse gas standards[83] and receive credits through 2019 for complying with the National Highway Traffic Safety Administration’s fuel economy standards. For these reasons, a rapidly growing proportion of vehicle sales are FFVs; in 2011, 17 percent of all cars sold in the United States were FFVs,[84] and GM has pledged that half of its new cars sold in 2015 will be FFVs.[85] But many FFV owners are not aware they have an FFV,[86] and consumption of E85 has been very low. Table 2 shows capacity of the U.S. FFV fleet to consume E85 compared with actual E85 consumption; on average, only about 1 percent of the average FFV’s fuel consumption is E85.

Table 2. FFV consumption of E85 fuel, vehicle population, and percent E85 usage

YEAR	E85 FUEL CONSUMPTION[87] (MILLION GALLONS)	E85 FFV VEHICLE POPULATION[88] (MILLION VEHICLES)	ANNUAL VOLUME OF E85 USE (GALLON E85/FFV)	ANNUAL E85 CONSUMPTION BY FFVS, AS % OF TOTAL FFV FUEL CONSUMPTION[89,90]
1998	2	0.1	12.3	1.4%
1999	4	0.5	8.9	1.0%
2000	12	0.9	13.7	1.6%
2001	15	1.4	10.9	1.3%
2002	18	2.1	8.8	1.0%
2003	26	2.8	9.3	1.1%
2004	32	3.4	9.2	1.1%
2005	38	4.1	9.2	1.1%
2006	44	5.1	8.7	1.1%
2007	54	6.2	8.8	1.1%
2008	62	7.3	8.6	1.1%
2009	71	8.4	8.5	1.1%
2010	90	9.7[91]	9.3	1.1%

There are several possible reasons behind the low consumption of E85. E85 is generally more expensive than gasoline on an energy basis,[92] so it costs more per mile. For example, one gallon of a mixture of 80 percent ethanol and 20 percent gasoline has 73 percent of the energy content of pure gasoline and 74 percent of the energy content of E10. If a fueling station sells E10 for $3.00 per gallon, E85 should be priced at $2.23 per gallon for an equivalent price per mile. In practice, E85 is often sold only about 10 percent cheaper than E10 on a volume basis;[93] $2.70 in this example. An FFV owner looking to minimize refueling costs in this market would keep fueling with E10 because it's cheaper per mile driven. The lower energy density of ethanol also means that a consumer cannot drive as far on a tank of E85, and must refuel more often than they would if using E10. Considering this inconvenience, it is likely that E85 would need to be priced even lower (perhaps $2.00 per gallon in this example) to attract consumers. Note that, as described above, CO_2 emissions are similar for ethanol and gasoline on an energy-equivalent basis, and so these differences in energy density are not significant from a climate perspective.

Another important factor in the low consumption of E85 is a geographical mismatch between location of FFVs and fueling stations offering E85. As an analysis from Iowa State University shows, most E85 is offered in the Midwest, while Texas, California, and the Southeastern United States have large numbers of FFVs with no access to high ethanol fuel.[94] Finally, some drivers may simply be resistant to using a different fuel or may even fail to realize that they are driving FFVs.

Small Engines and Off-road Applications

Equipment With Small Gasoline Engines

Equipment with small engines—including lawnmowers, snowmobiles, hand-trimmers, and other tools—typically operates with open loop systems (i.e., no systematic air/fuel adjustment) and is designed to deliver a *rich* fuel mixture (low air/fuel ratio, the opposite of enleanment). The evaporative cooling of the extra fuel helps keep the engine from overheating and prolongs the life of the equipment.[95]

Most manufacturers of equipment using small engines permit usage of ethanol blends up to E10 under warranty.[96] Because these systems cannot adjust the air/fuel ratio, enleanment is a major concern. Tests by NREL confirmed that enleanment did occur in several types of equipment with small gasoline engines, leading to significant increases in exhaust temperature when operating on E15 compared with E0 (10–50°F) and with E20 compared with E0 (20–70°F).[97] However, the exhaust temperature was only 5–10°F higher when comparing E15 operation with E10, suggesting that the most pronounced effect of ethanol on exhaust temperature occurs between E0 and E10. Like most of the vehicle tests discussed in the previous section, NREL's test on small engines found only slight changes in emissions, with NOx increasing and hydrocarbons/carbon monoxide decreasing with higher blends of ethanol.

A more serious problem is that three handheld trimmers in this study experienced unintentional clutch engagement when operating on higher ethanol blends. Because equipment with small engines typically run on a rich fuel mixture, enleanment from ethanol can actually lead to more efficient combustion and higher power than when operating on pure gasoline. In the case of the handheld trimmers, the resulting higher idle speed forced the clutch to engage and turned on the equipment. This effect could be dangerous if it occurred in some types of equipment, such as chainsaws. Too much enleanment could also lead to misfire,[98] and thus higher ethanol blends increase the chances that misfire may occur under some operating conditions for equipment with a tight operating tolerance.

Enleanment in small engines can be addressed to some extent by adjusting the choke to reduce the amount of air that is admitted into the engine or by using larger carburetor jets to increase the amount of fuel delivered; either of these changes would help lower the air/fuel ratio.[99] It is unlikely, and unadvisable, that owners would make these adjustments on existing equipment, but new equipment could potentially be designed to safely operate on higher blends of ethanol if desired. Such new equipment may, however, have higher hydrocarbon and carbon monoxide emissions if the small engine is fueled with gasoline or E10 instead of the higher ethanol blend for which it was designed.

As with cars, higher ethanol blends could damage materials that were not designed for them. However, in the NREL study no negative effects on materials were observed. Most of these engines have a short service life, in terms of hours of use, which also minimizes the impacts of material damage. In principle, materials damage to equipment and vehicles with small engines should not differ from that in cars because in both cases the fuel lines and other components are exposed to ethanol most of the time, whether in operation or not.

Motorcycles

Because emission standards for motorcycles are less strict than for cars, not all motorcycles are equipped with catalytic converters, and some motorcycles have a more basic type of catalytic converter that does not require accurate oxygen sensors and systematic adjustment of the air/fuel ratio. Fifty-eight percent of motorcycle models for 2014 operate on an open loop system, and almost half of these are open loop with multiple cylinders.[100] NREL reported that equipment with multiple cylinders experienced more severe problems with enleanment because, in some cases, the cylinders experienced different air/fuel ratios.[101] For the approximately 40 percent of motorcycle models with closed loop systems, fueling on E15 or E20 should not carry a significant risk for overheating or increased emissions, although materials compatibility could still be an issue. Because many motorcycle owners probably don't know if their vehicle has a closed loop system or not, in general it is advisable for motorcycles to avoid fueling on higher blends of ethanol. While refueling with E10 probably does lead to enleanment in some motorcycles, the effect is likely small enough not to result in serious problems.

Aviation and Marine

Commercial ships and aircraft do not use gasoline, and so there is little potential for uptake of ethanol blends in these sectors over the near to medium term. Instead of ethanol, there is the potential for "drop-in" biofuels[102] to be blended with jet fuel (a kerosene-based fuel somewhat similar to diesel). In this case, because the biofuel must be chemically similar to jet fuel, blending should not create any problems. Commercial ships typically operate on bunker fuel (an inexpensive and dirty petroleum derivative) and because low fuel cost is very important to shipping, this sector has not yet made any significant steps toward increased blending of biofuels with marine fuel.

Some small recreational boats have gasoline engines. Because these tend to have open loop control, enleanment is a problem, as in small engines and older vehicles. Testing E15 at wide open throttle, when enleanment is most likely to occur, NREL observed enleanment, high temperatures in the exhaust and catalyst, and degradation of metals, elastomers, and valves in small boats, compared with use at E0.[103] In an Australian study, some small boats stalled when operated on E10 and E20.[104] These results indicate that E15 and E20 should not be used in small boats, although additional research could be conducted to confirm these findings. Presumably, new boats could be designed to operate on higher blends of ethanol, with similar adjustments to the choke and carburetor as described for small engines, and using ethanol-compatible materials. However, as with small engines, marine engines designed for higher ethanol blends would have higher hydrocarbon and carbon monoxide emissions if fueled with gasoline or E10. Also, the constant exposure to water and humidity in marine applications could exacerbate problems with ethanol adsorption of water, increasing the risk of phase separation.

Unlike commercial planes, some small personal aircraft do operate on gasoline, called "Avgas." Unlike motor gasoline in the United States, Avgas still uses lead additives to boost the octane rating, and because lead is toxic, some have argued for ethanol to replace lead as an octane improver in Avgas.[105] New aircraft could potentially be designed to accommodate ethanol blends, and aircraft operating on pure or almost pure ethanol have already been developed.[106,107] However, existing aircraft running on Avgas may have significant compatibility issues with ethanol, and further research must be conducted before recommending ethanol blends in small airplanes.

Infrastructure

In order to supply higher blends of ethanol to vehicles, compatible infrastructure must be in place. Here, we discuss the effects of ethanol on fuel dispensers, storage tanks, and pipelines. We also describe available technologies that can be used to adapt infrastructure to the supply of E15–E85.

Fuel Dispensers

Concern about using E15 with existing fuel dispensers centers around materials compatibility. An Oak Ridge National Laboratory (ORNL) study tested the effects of "aggressive" (i.e., contaminated) ethanol blends from E10–E25 on dispenser materials.[108] They found very little corrosion of metallic components with soaking in "aggressive" E10, E17, and E25, and higher ethanol blends were not associated with greater corrosion. When elastomers were soaked in fuel, they swelled, even with pure gasoline.[109] This swelling was greater in ethanol blends and some elastomers softened, indicating a reaction with the ethanol. The highest swell occurred with soaking in E10 or E17, with less swelling at E25, suggesting potential damage may be greatest at lower blends of ethanol. Some of these elastomers have a flexible design, and new components could be made that are ethanol-compatible. Sealants leaked with E10 and E25, but simply wrapping the seals with Teflon tape was effective at preventing leaking.

Gilbarco, a major manufacturer of fuel dispensers, covers use of E15 under their warranty for new products and even retroactively extended this coverage to all dispensers sold since 2008.[110] This suggests that new dispensers, at least with this manufacturer, are already using materials compatible with E15, and it indicates an opportunity for some fueling stations with dispensers five years old or less to offer E15 immediately.[111] On the other hand, Underwriter Laboratories (UL), a major certification body for fueling infrastructure, only covers regular dispensers with the use of fuel up to E10 at this point,[112] and certification may be required by law for fuel dispensers, depending on location. So even though some existing dispensers may be able to handle E15, it is unlikely that many fueling station owners will supply E15 without modifications unless UL extends its certification for E10 dispensers to E15. UL has a separate certification available for dispensers designed for E25 or E85. Additional research would be required to determine whether regular dispensers produced today are compatible with blends higher than E15.

It is relatively inexpensive to retrofit existing dispensers for station owners with dispensers that are not currently warrantied for the use of higher blends of ethanol. Gilbarco sells a retrofit kit for $1,800 that allows use of blends up to E25.[113] Other estimates of retrofit cost are in the ballpark of $1,000–$4,000.[114]

Stations offering E15 would also need to offer E10 or E0 for older vehicles, motorcycles, small boats, and equipment with small engines. This will require a system to be put in place to reduce the risk of people accidentally using the wrong type of fuel; at a minimum, that would involve a campaign of driver education and a clear system of labeling to discourage misfueling.

Use of ethanol blends above E25 requires retrofitting or installing new dispensers; both of these options are available, but are more expensive than retrofitting dispensers for use with E15–E25. In addition, it is likely that the fuel station owner would have to replace or retrofit their fuel storage tanks (discussed in the next section). From a survey and literature review, NREL determined that the cost of retrofitting both the storage tank and dispensers for E85 would be around $11,000 per station, and replacing these parts with E85-compatible equipment would cost around $59,000.[115] If stations are to offer both E10 and higher ethanol blends, they may require additional storage tanks rather than just replacing existing ones, increasing the cost. Thus, although the technology for dispensing high-ethanol fuel is available, the conversion cost may discourage fuel station owners from offering E85. This cost is partially offset by a federal investment tax credit for the installation of E85 fueling equipment that is set to expire at the end of 2013.

Underground Storage Tanks (USTs)

Little research has been conducted specifically on the effects of ethanol on USTs. A second study by ORNL[116] relied heavily on the previous ORNL study discussed above on dispenser materials and how ethanol would affect similar materials in USTs. There are potential problems with steel tanks, and literature reviewed by ORNL suggested corrosion inhibitors may be necessary to prevent the serious problem of "stress corrosion cracking" (SCC) in USTs. Other materials also had mixed results. Fiberglass-reinforced plastic was found to handle E15 well but not E50 or E85. Most flexible plastic piping and elastomers used in USTs did not experience significant damage with E15. Interestingly, this study found a significant difference in materials durability between E0 and E10, but not between E10 and E15. This suggests that some problems with ethanol that may affect USTs have likely already occurred, but that increasing the ethanol percentage to E15 may not make matters worse. When preparing for a switch to E15 in existing USTs, it is necessary to first clean out the tank to minimize water contamination. To handle E85, USTs would probably need to be more substantially retrofitted or replaced.

Pipelines

Ethanol blends are typically not transported via pipeline in the United States—pure gasoline is piped, and ethanol is shipped in trucks, and the two are blended together at the destination. But in the future, greater volumes of ethanol could potentially be transported by pipeline from the Midwest, where most ethanol is produced, to other parts of the country. As with USTs, there are serious concerns about ethanol causing SCC in pipelines.[117,118] Oxygen in ethanol exacerbates corrosion by protecting most of the steel surface and channeling degradation to isolated areas of steel, and by absorbing electrons emitted from the steel during corrosion. These problems can be addressed by lining the pipeline with a protective material or by adding corrosion inhibitors to the fuel.[119]

Water contamination is also a potential issue with ethanol in pipelines because water absorbed by ethanol may contain rust and other particulates that accumulate during transportation of gasoline. The presence of such contaminants can be minimized by cleaning out a pipeline before transporting ethanol through it.[120] In addition, the risk of water contamination is reduced when ethanol blends are transported regularly, instead of alternating batches of ethanol blends and pure gasoline. Lastly, filters can be added to remove contaminants when fuel exits the pipeline.[121] According to the Pipeline Research Council International,[122] E15 can be transported through pipelines without any modifications, and E20 can be transported if corrosion inhibitors are added to the fuel. The effects of corrosion inhibitors on vehicle emissions and material compatibility should be investigated before they are used routinely.

There is little research done on the effects of transporting ethanol blends above E20 through pipelines, but it appears to be possible. Brazil has been transporting pure ethanol through pipelines since the 1970s. Although some seals and elastomers have had to be replaced, Petrobras, Brazil’s national oil company, claims they have not experienced SCC in their pipelines, even without installing liners.[123] In the United States, Kinder Morgan has been transporting alternating batches of ethanol and gasoline in Florida since 2008,[124] and recently has been working on similar projects in other states.[125]

The U.S. Department of Energy (DOE)[126] has considered the feasibility of constructing an ethanol-only pipeline from the Midwest to the East Coast. Although the cost would be significant, it would not be prohibitive if demand for ethanol on the East Coast were high enough. The pipeline would have to transport 4.1 billion gallons of ethanol per year to be cost competitive, compared with expected demand of 2.8 billion gallons per year. Like all new pipelines, a dedicated ethanol pipeline would likely face delays from siting, permitting, financing, and regulation.

Timeline for Consumption of Higher Blends of Ethanol

In this section, we discuss the amount of time needed to make necessary technological changes to vehicles and infrastructure in order to consume higher blends of ethanol. We compare this timeline with projections of RFS2 implementation.

Timeline for Technological Changes in Vehicles and Infrastructure

Vehicles: The major concerns with using higher blends of ethanol in vehicles are increased emissions, material incompatibility, and phase separation of water and ethanol from gasoline. The risk of phase separation is limited in general and could be addressed by adding solubility improvers to fuel. Cars manufactured in 2001 and later have the proper controls and materials to handle E15 and likely E20 and do not need any modification. At the time of writing, it is estimated that at least 50 percent of the car fleet is in this age class, and by 2022, virtually all cars driven in the United States will be capable of operating on E15.[127,128] Many cars manufactured today are FFVs, and other cars could relatively easily be retrofitted to be flex-fuel. Not accounting for other factors like cost, the U.S. fleet could theoretically be technologically ready to consume significant amounts of E15 and E85 within a few years.

Dispensers and tanks: Some current fuel dispensers appear to be compatible with E15, and it is easy and relatively inexpensive to convert existing dispensers to handle E15–E25. Gilbarco advertises that this conversion takes only three hours. Retrofitting or replacing dispensers to be compatible with E85 may take longer, but not likely more than a few days. A system to minimize the risk of misfueling must be developed. It is difficult to know how long this would take, as EPA has not proposed such a system yet; for the purposes of the projections below, we assume that, only considering technical issues, it could be on the order of one to two years. Some existing underground storage tanks may be compatible with E15, but to accommodate higher blends would require retrofits or replacements. We were unable to find estimates of how long it would take to replace these tanks, but assume it should not be longer than a few months in most circumstances.

Pipelines: Existing pipelines may already be compatible with E15 and may be able to accommodate E20 if corrosion inhibitors are added to the fuel. To ensure compatibility with

E15 or higher blends, the pipeline may also need to be cleaned and have a liner added to the interior. It has been estimated that the pace of pipeline cleaning is 4 to 15 feet per second;[129] at a rate of 10 feet per second, a 1,000-mile pipeline would take only six days to clean. New pipelines may also be constructed for the dedicated transport of ethanol, a process that would likely take a few years. For example, the Trans Alaska Pipeline System, one of the largest in the United States, was constructed in about three years.[130] It should also be noted that pipelines are not necessary for the movement of higher blends of ethanol, which are currently—and could continue to be—transported primarily by rail and truck.[131,132]

Ethanol Consumption Under Projections of RFS2 Implementation

In order to test whether or not technical barriers constrain implementation of the RFS2, in this section we compare the rate at which ethanol blends could technically be scaled up against three projections of RFS2 implementation:

- implementation of the RFS2 targets for 2014–2022 as originally set in the statute;
- revised implementation of the RFS2 with greatly reduced cellulosic volumes, following EPA's annual volume rulemakings for 2010–2013; and
- immediate repeal of the RFS2.

Original RFS2: The RFS2 targets as originally set in the statute are for 18.15 billion gallons of total renewable fuel in 2014, ramping up to 36 billion gallons in 2022 (Figure 2). Most of this increase is from rising targets for cellulosic biofuel, or biofuel produced from non-food plant material like wood, leaves, and straw. In this projection, we assume all biofuel categories other than biomass-based diesel will be fulfilled with ethanol. Note that this is a maximum-ethanol projection. If significant volumes of drop-in fuels are produced instead of ethanol, the amount of ethanol required will be lower.

Revised RFS2: EPA has revised the cellulosic requirement downward in each year of implementation of the RFS2 due to slow commercialization of the industry[133] and is very likely to continue to do so. For this projection, we assume that EPA will continue to waive most of the cellulosic mandate, and only 1 percent of the volumes specified in the statute will be fulfilled in 2014, scaling up to 5 percent in 2022, an absolute increase from 17 to 800 million gallons. Given the history of the industry, we believe that this projection may still be quite optimistic. In 2012, only 20,000 gallons of cellulosic biofuel were registered under the RFS2 credit system (i.e., Renewable Identification Numbers, or RINs), less than 0.005 percent of the original target for 500 million gallons. We assume EPA will continue to keep the original targets for the other categories of biofuel, as they have done in the past. Lastly, we assume the biomass-based diesel mandate will be maintained at the 2013 volume of 1.28 billion gallons per year (1.92 billion gallons of ethanol equivalent) and that the rest of the RFS2 mandate is filled with ethanol. The requirement for ethanol consumption under this projection is shown as "Revised RFS2 projection" in Figure 2.

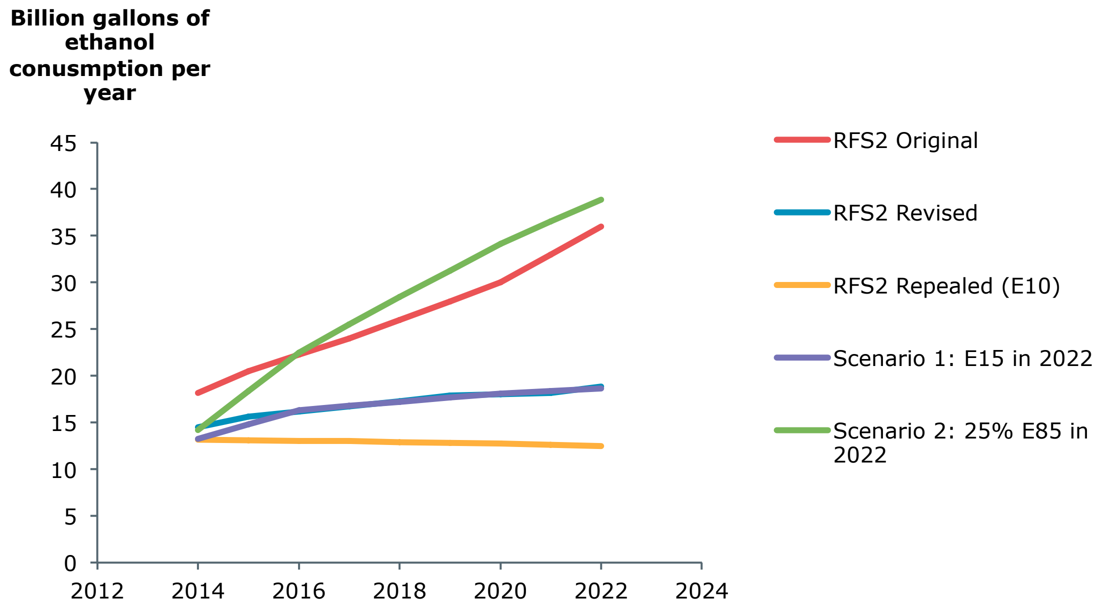
RFS2 repeal: In this projection, we assume the RFS2 is repealed immediately; it represents ethanol consumption with no federal policy support. Some analysts project that ethanol consumption would not substantially change from the present if the RFS2 were repealed. Without a policy driver, it is unlikely ethanol consumption would increase unless oil prices rise significantly. Some also consider it unlikely that consumption would decrease unless oil prices drop significantly, because the ethanol industry is already mature and cost competitive, and ethanol has value as an octane booster in gasoline. A study commissioned by DOE during the 2012 drought[134] estimated that ethanol prices would have to rise more than 26 cents per gallon in order for fuel refiners and blenders to use 33 percent less ethanol in gasoline. At the same time, agricultural economists estimated that a waiver on the 2012 renewable fuel mandate (mostly corn ethanol) would have little impact on corn ethanol consumption, even in a year of relatively high corn prices.[135] Following the work of these analysts, we present the "RFS2 repeal" scenario as the "E10" line in Figure 2. We believe this is at the high end of the likely range for ethanol supply in the event of RFS repeal. Projected consumption of E10 follows an expected slight decline in gasoline consumption with improved vehicle efficiency under the revised Corporate Average Fuel Economy (CAFE) standards.

In addition to these three RFS2 projections, Figure 2 shows two scenarios for the consumption of ethanol to 2022, considering only technical barriers:

Scenario 1: E15 in 2022. This assumes 1 percent of gasoline consumed in 2014 is E15, ramping up quickly to 50 percent in 2016 (which is technically feasible through infrastructure retrofits, etc.), and then finally rising to 100 percent of all fuel in 2022; prior to 2022, the remainder of gasoline consumed is E10. This scenario follows the estimation above that more than 50 percent of the current U.S. car fleet was manufactured 2001 and later, and thus can safely operate on E15; it assumes that the share of the fleet manufactured in 2001 and later rises to virtually 100 percent by 2022.

Scenario 2: 25 percent E85 in 2022. This scenario assumes 1 percent of gasoline will be sold as E85 in 2014, and this rises to 25 percent in 2022. Here, E85 is assumed on average to be 75 percent ethanol in practice. The remainder of gasoline follows the trend of "E15 in 2022" of 1 percent E15 in 2014 rising to 100 percent E15 in 2022. Technically, vehicles and infrastructure could be modified to accommodate E85 even faster than this projection, but there are significant non-technical barriers to such a scenario.

Figure 2. Two scenarios of U.S. ethanol consumption—with standard road fuel composed of 100 percent E15 in 2022 or 25 percent E85 in 2022—as compared with projections of original, revised, and repealed RFS2 requirements from the present to 2022. The consumption scenarios are technically achievable but do not reflect significant barriers such as cost, regulation, legality, and consumer acceptance.



From Figure 2, we see that scaling up E15 to 100 percent market penetration would be approximately sufficient to satisfy the "revised RFS2" scenario after 2015. Scaling up both E15 and E85 (the latter to 25 percent penetration) would be sufficient even to allow fulfillment of the "original RFS2" projection from 2017 onward, and would be much more than enough to allow the "revised RFS2" scenario to be fulfilled starting in 2015. Although both of these scenarios for the consumption of ethanol through E15 and E85 are technically possible given today's availability of vehicle and materials technology, the "E15 in 2022" scenario would require fewer modifications to infrastructure. The E85 scenario would require retrofits and potentially replacement of pipelines, storage tanks, and dispensers. Current trends in car sales suggest the U.S. vehicle fleet will be technologically ready to consume the amounts of ethanol in these two scenarios. This clearly indicates that technical capacity does not stand in the way of being able to consume adequate ethanol volumes to allow compliance with the RFS2 in the medium timeframe. On the other hand, our scenarios show that, even without considering non-technical barriers, it may be difficult to comply with the RFS2 in 2014–2016, because the necessary infrastructure is not yet in place.[136,137]

Conclusions

Summary of Technical Barriers to the Consumption of Higher Ethanol Blends

This study reviews technical barriers to the consumption of blends of ethanol above 10 percent in vehicles and infrastructure. Claims that E15 cannot be safely used in newer (2001 and later) vehicles focus on a set of studies by the CRC that observed leaks, engine failure, and elevated pollutant emissions in a small number of cars. In one study, cars were tested on "aggressive" E20 contaminated with acid and other corrosive substances, which may have swayed the results. These studies tested a small number of cars and were intended only as indications of where further study was needed. Interpreting these results in the context of a number of other studies—which found no significant damage to vehicles with E15 and E20—we conclude that vehicles model year 2001 or later can safely consume E15. Although there is some evidence showing vehicles older than 2001 can tolerate ethanol blends up to E30, these vehicles do not have the same technological advantages of newer cars and it is likely not prudent to use higher ethanol blends in them. FFVs that can operate on E0–E85 are currently being produced at high volume, and non-FFV vehicles can be retrofitted.

Fueling infrastructure may have material incompatibility with ethanol, especially with regard to elastomers (that is, rubber- or plastic-like materials). Still, there is evidence that E15 may be safely used with some existing fuel dispensers and pipelines, if those dispensers and pipelines are cleaned before ethanol is transported. Technology is available for the production of new dispensers, storage tanks, and pipelines that can accommodate ethanol blends E15–E85, and many existing infrastructure elements can be retrofitted for this purpose. As multiple blends become available, at a minimum it will be necessary to develop and enforce a clear system of labeling to discourage misfueling, as well as to undertake driver education.

Equipment with small gasoline engines, such as lawnmowers, snowmobiles, and small boats, has more serious compatibility issues with higher ethanol blends. New equipment can be designed to operate on these blends, but retrofitting existing equipment is not likely to be practical. The possibility of replacing lead additives with ethanol in aviation gasoline for small aircraft should be studied further.

Projections for Ethanol Consumption to 2022

We present three projections for the implementation of the RFS2: original RFS2 targets, revised RFS2 requirement, and RFS2 repeal. Under a technically feasible scenario of 1 percent E15 consumption, scaling up to 100 percent E15 in 2022, we find that the revised

RFS2 requirement could be satisfied after 2015. E85 could also be rolled out quickly, and under a conservative, technically feasible scenario scaling up to 25 percent E85 consumption in 2022, we show that even the original RFS2 target of 36 billion gallons of biofuel in 2022 could be met.

Our results indicate that technical issues are not the real barriers to the consumption of higher blends of ethanol. However, this study did not take into account a myriad of other critical factors, including but not limited to: cost, politics, regulation, and consumer acceptance. Actual achievement of the "E15 in 2022" or "25 percent E85 in 2022" scenarios would require substantial subsidies for ethanol fueling infrastructure and immediate solutions to all political, regulatory, and social barriers. Thus, our scenarios should not be interpreted as expectations for real outcomes, but as an illustration that such outcomes are not constrained by technological barriers. Moreover, criticism of ethanol and the RFS2 goes beyond concerns about the feasibility of consumption; corn ethanol in particular has been widely criticized for driving increases in food prices, causing food price volatility, and leading to indirect land use change greenhouse gas emissions.[138] Such outcomes may be largely avoided if additional biofuel under RFS2 is produced from non-food feedstocks.

Endnotes

[1] An elastomer is an elastic polymer. These rubber or plastic-like materials are used in a variety of car parts, including seals, o-rings, and other gaskets designed to prevent fluid leakage.

[2] This summary and timeline does not account for non-technical barriers, such as the cost of new equipment and retrofits or the higher cost per mile of ethanol fuel; these issues, along with other non-technical barriers, will seriously limit the application of technical solutions to higher ethanol blends.

[3] Ethanol Producer Magazine. Minnesota extends E20 mandate to start in 2015. 2012; Available from: http://ethanolproducer.com/articles/8767/minnesota-extends-e20-mandate-to-start-in-2015.

[4] Pollution is reduced by leaning out the air/fuel mixture. Enleanment is discussed in the next section on Vehicle Compatibility.

[5] Environmental Protection Agency, Regulation of Fuels and Fuel Additives: 2013 Renewable Fuel Standards, Final Rule2013, EPA-HQ-OAR-2012-0546: Federal Register.

[6] Ethanol Producer Magazine. Minnesota extends E20 mandate to start in 2015. 2012; Available from: http://ethanolproducer.com/articles/8767/minnesota-extends-e20-mandate-to-start-in-2015.

[7] This requirement was enacted despite the fact that EPA has not yet granted a waiver for fuels with more than 15 percent ethanol.

[8] Environmental Protection Agency, Partial Grant and Partial Denial of Clean Air Act Waiver Application Submitted by Growth Energy To Increase the Allowable Ethanol Content of Gasoline to 15 Percent; Decision of the Administrator, 2010, EPA-HQ-OAR-2009-2011; FRL-9215-5: Federal Register.

[9] Environmental Protection Agency, Partial Grant of Clean Air Act Waiver Application Submitted by Growth Energy To Increase the Allowable Ethanol Content of Gasoline to 15 Percent; Decision of the Administrator, 2011, EPA-HQ-OAR-2009-0211; FRL-9258-6: Federal Register.

[10] AAA. Testimony in U.S. House of Representatives Energy and Power Subcommittee hearing: Overview of the Renewable Fuel Standard: Stakeholder Perspectives. 2013 [cited 2013 October 26]; Available from: http://energycommerce.house.gov/hearing/overview-renewable-fuel-standard-stakeholder-perspectives.

[11] Alliance of Automobile Manufacturers. Testimony in U.S. House of Representatives Energy and Power Subcommittee hearing: Overview of the Renewable Fuel Standard: Stakeholder Perspectives. 2013 [cited 2013 October 26]; Available from: http://energycommerce.house.gov/hearing/overview-renewable-fuel-standard-stakeholder-perspectives.

[12] The DOE tests were conducted by Oak Ridge National Laboratory.

[13] Almost all heavy-duty vehicles in the United States operate on diesel and so are not discussed here.

[14] Sluder, C. S. & West, B. H., Preliminary Examination of Ethanol Fuel Effects on EPA's R-factor for Vehicle Fuel Economy, Produced for the Department of Energy2013, Oak Ridge National Laboratory.

[15] Stein, R. A., Anderson, J. E. & Wallington, T. J., An Overview of the Effects of Ethanol-Gasoline Blends on SI Engine Performance, Fuel Efficiency, and Emissions. SAE International Journal of Engines, 2013. 6(1): p. 470-487.

[16] Knoll, K. et al., Effects of Intermediate Ethanol Blends on Legacy Vehicles and Small Non-Road Engines, Report 1 - Updated, NREL/TP-540-43543; ORNL/TM-2008-1172009, National Renewable Energy Laboratory. p. 135.

[17] For flex-fuel vehicles, making fuel tanks larger in new vehicles does not solve the range reduction problem, as regardless of tank size, the vehicle will always travel much farther on gasoline or low ethanol blends than on E85.

[18] Higher ethanol blending raises the octane rating of gasoline and provides much higher evaporative cooling of the intake charge. These effects can allow the engine to operate more efficiently, by enabling the compression ratio in a car's engine to be increased and higher levels of turbocharger boost with smaller engines. Operators of such cars would have to exercise caution as misfueling on lower ethanol blends could lead to engine knocking or greatly reduced performance.

[19] Environmental Protection Agency, Control of Air Pollution From Motor Vehicles: Tier 3 Motor Vehicle Emission and Fuel Standards, 2013, EPA-HQ-OAR-2011-0135; FRL-9785-5: Federal Register. p. 377.

[20] Stein, R. A., Anderson, J. E. & Wallington, T. J., An Overview of the Effects of Ethanol-Gasoline Blends on SI Engine Performance, Fuel Efficiency, and Emissions. SAE International Journal of Engines, 2013. 6(1): p. 470-487.

[21] This effect is mitigated to some extent by the much higher evaporative cooling provided by ethanol compared with gasoline.

[22] A catalytic converter is a device downstream of the engine containing precious metals that convert harmful pollutants like nitrous oxides and carbon monoxide in the exhaust into stable gases like nitrogen and carbon dioxide.

[23] In 1981, EPA started requiring all new vehicles to be equipped with a three-way catalytic converter, which requires an oxygen sensor with feedback to the fuel injector.

[24] Bonnema, G. et al., Use of Mid-Range Ethanol/Gasoline Blends in Unmodified Passenger Cars and Light Duty Trucks, 1999, Minnesota Center for Automotive Research, Minnesota State University. p. 8.

[25] Mondt, J. R., Cleaner cars: the history and technology of emission control since the 1960s. 2000, Warrendale, Pa: Society of Automotive Engineers. p. 262.

[26] Modern vehicles operate under open loop conditions when in full throttle (e.g., when accelerating very quickly) primarily to provide excess fuel to reduce combustion temperatures and prevent catalyst damage from excessive temperatures. A secondary benefit is 3–4 percent higher power output. Manufacturers also run rich air/fuel mixtures (with a relatively high ratio of fuel to air) during cold starts at ambient temperatures below 45–50°F, as fuel does not evaporate as well at cold temperatures and a richer mixture is needed to ensure that enough fuel evaporates to support combustion. During cold starts at warmer temperatures, where fuel evaporation is not a concern, manufacturers will run lean to reduce emissions before the catalytic converter reaches operating temperatures and will increase idle speed to heat the catalytic converter faster and bring it to operating temperatures as quickly as possible.

[27] Knoll, K. et al., Effects of Intermediate Ethanol Blends on Legacy Vehicles and Small Non-Road Engines, Report 1 - Updated, NREL/TP-540-43543; ORNL/TM-2008-1172009, National Renewable Energy Laboratory. p. 135.

[28] West, B. H., Sluder, C. S., Knoll, K., Orban, J. & Feng, J., Intermediate Ethanol Blends Catalyst Durability Program, ORNL/TM-2011-2342012, Oak Ridge National Laboratory.

[29] Bechtold, R. et al., Technical Issues Associated with the Use of Intermediate Ethanol Blends (>E10) in the U.S. Legacy Fleet: Assessment of Prior Studies, ORNL/TM-2007/372007, Oak Ridge National Laboratory. p. 67.

[30] West, B. H., Sluder, C. S., Knoll, K., Orban, J. & Feng, J., Intermediate Ethanol Blends Catalyst Durability Program, ORNL/TM-2011-2342012, Oak Ridge National Laboratory.

[31] Bechtold, R. et al., Technical Issues Associated with the Use of Intermediate Ethanol Blends (>E10) in the U.S. Legacy Fleet: Assessment of Prior Studies, ORNL/TM-2007/372007, Oak Ridge National Laboratory. p. 67.

[32] Knoll, K. et al., Effects of Intermediate Ethanol Blends on Legacy Vehicles and Small Non-Road Engines, Report 1 - Updated, NREL/TP-540-43543; ORNL/TM-2008-1172009, National Renewable Energy Laboratory. p. 135.

[33] The CRC is a nonprofit organization that directs engineering and environmental studies on vehicles and fuels.

[34] Kleeberg, H., Intermediate-Level Ethanol Blends Engine Durability Study, Prepared for: Coordinating Research Council, Inc., CRC Project: CM-136-09-1B2012, Coordinating Research Council, Inc.: Alpharetta, GA. p. 102.

[35] These results omitted one vehicle that that failed all tests, including E0.

[36] Orbital Engine Company, Market Barriers to the Uptake of Biofuels Study Testing Gasoline Containing 20 percent Ethanol (E20), Phase 2B Final Report to the Department of the Environment and Heritage2004, Orbital Engine Company. p. 193.

[37] Bonnema, G. et al., Use of Mid-Range Ethanol/Gasoline Blends in Unmodified Passenger Cars and Light Duty Trucks, 1999, Minnesota Center for Automotive Research, Minnesota State University. p. 8.

[38] Orbital Australia Pty Ltd, Assessment of the Operation of Vehicles in the Australian Fleet on Ethanol Blend Fuels, Report to Department of the Environment and Water Resources2007, Commonwealth of Australia: Canberra, Australia. p. 230.

[39] Formaldehyde and acetaldehyde are organic compounds produced from ethanol combustion; gasoline does not produce as much of these compounds because of its chemical structure.

[40] Stein, R. A., Anderson, J. E. & Wallington, T. J., An Overview of the Effects of Ethanol-Gasoline Blends on SI Engine Performance, Fuel Efficiency, and Emissions. SAE International Journal of Engines, 2013. 6(1): p. 470-487.

[41] Knoll, K. et al., Effects of Intermediate Ethanol Blends on Legacy Vehicles and Small Non-Road Engines, Report 1 - Updated, NREL/TP-540-43543; ORNL/TM-2008-1172009, National Renewable Energy Laboratory. p. 135.

[42] West, B. H., Sluder, C. S., Knoll, K., Orban, J. & Feng, J., Intermediate Ethanol Blends Catalyst Durability Program, ORNL/TM-2011-2342012, Oak Ridge National Laboratory.

[43] Stein, R. A., Anderson, J. E. & Wallington, T. J., An Overview of the Effects of Ethanol-Gasoline Blends on SI Engine Performance, Fuel Efficiency, and Emissions. SAE International Journal of Engines, 2013. 6(1): p. 470-487.

[44] Ibid.

[45] Environmental Protection Agency, Integrated Science Assessment for Particulate Matter, 2009, National Center for Environmental Asessment-RTP Division: Research Triange Park, NC. p. 2228.

[46] Haskey, H. M., Liberty, T. F. & McClement, D., Fuel Permeation From Automotive Systems, Prepared for California Environmental Protection Agency, Air Resources Board, and Coordinating Research Council, Inc.2004, Coordinating Research Council, Inc. p. 86.

[47] Stein, R. A., Anderson, J. E. & Wallington, T. J., An Overview of the Effects of Ethanol-Gasoline Blends on SI Engine Performance, Fuel Efficiency, and Emissions. SAE International Journal of Engines, 2013. 6(1): p. 470-487.

[48] Andersen, V. F., Anderson, J., Wallington, T., Mueller, S. & Nielsen, O. J., Vapor pressures of alcohol−gasoline blends. Energy & Fuels, 2010. 24(6): p. 3647-3654.

[49] Haskew, H. M. & McClement, D., Fuel Permeation from Automotive Systems: E0, E6, E10, E20, and E85, 2006, Coordinating Research Council: Alpharetta, GA. p. 58.

[50] Orbital Australia Pty Ltd, Assessment of the Operation of Vehicles in the Australian Fleet on Ethanol Blend Fuels, Report to Department of the Environment and Water Resources2007, Commonwealth of Australia: Canberra, Australia. p. 230.

[51] Consumer Reports. Warranties void on cars burning E15, say automakers. 2007 [cited 2013 Octobr 26]; Available from: http://www.consumerreports.org/cro/news/2011/07/warranties-void-on-cars-burning-e15-say-automakers/index.htm.

[52] McCormick, R. L., Yanowitz, J., Ratcliff, M. & Zigler, B. T., Review and Evaluation of Studies on the Use of E15 in Light-Duty Vehicles, Prepared for the Renewable Fuels Association2013, National Renewable Energy Laboratory: Golden, CO. p. 53.

[53] Bechtold, R. et al., Technical Issues Associated with the Use of Intermediate Ethanol Blends (>E10) in the U.S. Legacy Fleet: Assessment of Prior Studies, ORNL/TM-2007/372007, Oak Ridge National Laboratory. p. 67.

[54] Knoll, K. et al., Effects of Intermediate Ethanol Blends on Legacy Vehicles and Small Non-Road Engines, Report 1 - Updated, NREL/TP-540-43543; ORNL/TM-2008-1172009, National Renewable Energy Laboratory. p. 135.

[55] Ricardo, I., Technical Assessment of E15 Use in 1994-2000 Model Year Vehicles, 2010, Ricardo, Inc.: Detroit, MI. p. 13.

[56] Knoll, K. et al., Effects of Intermediate Ethanol Blends on Legacy Vehicles and Small Non-Road Engines, Report 1 - Updated, NREL/TP-540-43543; ORNL/TM-2008-1172009, National Renewable Energy Laboratory. p. 135.

[57] Bonnema, G. et al., Use of Mid-Range Ethanol/Gasoline Blends in Unmodified Passenger Cars and Light Duty Trucks, 1999, Minnesota Center for Automotive Research, Minnesota State University. p. 8.

[58] Yuen, P., Beckett, J. & Villaire, W., Automotive Materials Engineering Challenges and Solutions for the Use of Ethanol and Methanol Blended Fuels. SAE Technical Paper, 2010(2010-01): p. 0729.

[59] McCormick, R. L., Yanowitz, J., Ratcliff, M. & Zigler, B. T., Review and Evaluation of Studies on the Use of E15 in Light-Duty Vehicles, Prepared for the Renewable Fuels Association2013, National Renewable Energy Laboratory: Golden, CO. p. 53.

[60] Knoll, K. et al., Effects of Intermediate Ethanol Blends on Legacy Vehicles and Small Non-Road Engines, Report 1 - Updated, NREL/TP-540-43543; ORNL/TM-2008-1172009, National Renewable Energy Laboratory. p. 135.

[61] Ricardo, I., Technical Assessment of E15 Use in 1994-2000 Model Year Vehicles, 2010, Ricardo, Inc.: Detroit, MI. p. 13.

[62] Knoll, K. et al., Effects of Intermediate Ethanol Blends on Legacy Vehicles and Small Non-Road Engines, Report 1 - Updated, NREL/TP-540-43543; ORNL/TM-2008-1172009, National Renewable Energy Laboratory. p. 135.

[63] Kleeberg, H., Intermediate-Level Ethanol Blends Engine Durability Study, Prepared for: Coordinating Research Council, Inc., CRC Project: CM-136-09-1B2012, Coordinating Research Council, Inc.: Alpharetta, GA. p. 102.

[64] McCormick, R. L., Yanowitz, J., Ratcliff, M. & Zigler, B. T., Review and Evaluation of Studies on the Use of E15 in Light-Duty Vehicles, Prepared for the Renewable Fuels Association2013, National Renewable Energy Laboratory: Golden, CO. p. 53.

[65] The leakdown test involves introducing compressed air into the cylinder and measuring the rate at which it leaks out.

[66] Coordinating Research Council & National Renewable Energy Laboratory, Durability of Automotive Fuel System Components Exposed to E20, 2011, Coordinating Research Council: Alpharetta, GA. p. 93.

[67] Knoll, K. et al., Effects of Intermediate Ethanol Blends on Legacy Vehicles and Small Non-Road Engines, Report 1 - Updated, NREL/TP-540-43543; ORNL/TM-2008-1172009, National Renewable Energy Laboratory. p. 135.

[68] Ricardo, I., Technical Assessment of E15 Use in 1994-2000 Model Year Vehicles, 2010, Ricardo, Inc.: Detroit, MI. p. 13.

[69] Knoll, K. et al., Effects of Intermediate Ethanol Blends on Legacy Vehicles and Small Non-Road Engines, Report 1 - Updated, NREL/TP-540-43543; ORNL/TM-2008-1172009, National Renewable Energy Laboratory. p. 135.

[70] Bonnema, G. et al., Use of Mid-Range Ethanol/Gasoline Blends in Unmodified Passenger Cars and Light Duty Trucks, 1999, Minnesota Center for Automotive Research, Minnesota State University. p. 8.

[71] Kittleson, D., Tan, A. & Zarling, D., Demonstration and Driveability Project to Determine the Feasibility of Using E20 as a Motor Fuel, Final report submitted to Minnesota Department of Agriculture2008, University of Minnesota: Minneapolis, MN. p. 63.

[72] Gramajo de Doz, M. B., Bonatti, C. M. & Sólimo, H. N., Water tolerance and ethanol concentration in ethanol-gasoline fuels at three temperatures. Energy & fuels, 2004. 18(2): p. 334-337.

[73] Waytulonis, R., Kittleson, D. & Zarling, D., E20 Effects in Small Non-Road SI Engines: A literature and Information Search, 2008, University of Minnesota, Center for Diesel Research: Minneapolis, MN. p. 47.

[74] Phase separation generally occurs at water concentrations of more than 0.5 percent in E10 and more than 4 percent in E85, and these water concentrations are unlikely to occur under normal conditions (although these tolerance limits decrease with lower temperatures).

[75] English, E. W., So What about Those E10 and E85 Fuels? A Discussion on Materials Compatibility, 2006, New England Interstate Water Pollution Control Commission: Lowell, Massachusetts.

[76] Krause, K., Water Phase Separation in Oxygenated Gasoline, D. Korotney, Editor 1995; Available from: http://www.epa.gov/otaq/regs/fuels/rfg/waterphs.pdf.

[77] Waytulonis, R., Kittleson, D. & Zarling, D., E20 Effects in Small Non-Road SI Engines: A literature and Information Search, 2008, University of Minnesota, Center for Diesel Research: Minneapolis, MN. p. 47.

[78] E85 is actually 51–83 percent ethanol in practice in the United States (Alternative Fuels Data Center). High ethanol blends do not evaporate as readily as gasoline, so the ethanol concentration must be reduced in colder weather to start the vehicle. Vehicles in Brazil can run up to E100, either using a separate fuel tank for gasoline used for cold starts or (for some newer models) without any gasoline at all.

[79] Heisner, B. M., E-85 and Flex-Fuel Technology, Presentations. Paper 2.2008; Available from: http://opensiuc.lib.siu.edu/auto_pres/2.

[80] Alternative Fuels Data Center. Flexible Fuel Vehicles. 2013 [cited 2013 October 26]; Available from: http://www.afdc.energy.gov/vehicles/flexible_fuel.html.

[81] Reuters. GM seeking more U.S. ethanol fueling stations. 2010 [cited 2013 October 26]; Available from: http://www.reuters.com/article/2010/02/16/gm-ethanol-idUSN1619509020100216.

[82] Hess, G., Renewable Fuels Face Bumpy Road, 2007: http://www.cen-online.org. p. 28-30.

[83] Energy Information Administration, Annual Energy Outlook 2012 with Projections to 2035, 2012, Energy Information Administration: Washington, DC. p. 252.

[84] Ibid.

[85] Green Car Congress. GM Reaffirms Commitment to Biofuels, Calls for Ongoing Commercialization and Infrastructure Support. 2010 [cited 2013 October 26, 2013]; Available from: http://www.greencarcongress.com/2010/02/stephens-20100216.html - more.

[86] Alternative Fuels Data Center. Flexible Fuel Vehicles. 2013 [cited 2013 October 26]; Available from: http://www.afdc.energy.gov/vehicles/flexible_fuel.html.

[87] Energy Information Administration. Annual Energy Review. 2012 [cited 2013 October 26]; Available from: http://www.eia.gov/totalenergy/data/annual/showtext.cfm?t=ptb1005.

[88] National Renewable Energy Laboratory. Data, Analysis and Trends: E85 FFVs in Use in U.S. (1998-2009). 2010 [cited 2013 April 20]; Available from: http://www.afdc.energy.gov/data/categories/vehicles.

[89] Calculated based on annual E85 volume and total fuel use.

[90] Oak Ridge National Laboratory, Transportation Energy Data Book: Edition 31, 2012, Department of Energy: Washington, DC. p. 422.

[91] Estimated from 2010 FFV production from Alternative Fuels Data Center.

[92] E85Prices.com. E85 Price Map. 2013 [cited 2013 October 26]; Available from: http://e85prices.com/.

[93] Ibid.

[94] Babcock, B. A. & Pouliot, S., Impact of Sales Constraints and Entry on E85 Demand, CARD Policy Brief 13-PB 122013, Iowa State University: Ames, IA. p. 9.

[95] Knoll, K. et al., Effects of Intermediate Ethanol Blends on Legacy Vehicles and Small Non-Road Engines, Report 1 - Updated, NREL/TP-540-43543; ORNL/TM-2008-1172009, National Renewable Energy Laboratory. p. 135.

[96] Waytulonis, R., Kittleson, D. & Zarling, D., E20 Effects in Small Non-Road SI Engines: A literature and Information Search, 2008, University of Minnesota, Center for Diesel Research: Minneapolis, MN. p. 47.

[97] Knoll, K. et al., Effects of Intermediate Ethanol Blends on Legacy Vehicles and Small Non-Road Engines, Report 1 - Updated, NREL/TP-540-43543; ORNL/TM-2008-1172009, National Renewable Energy Laboratory. p. 135.

[98] Misfire is when the spark occurs with no combustion of the air/fuel mixture in the cylinder, and so no power is delivered. This can happen with enleanment because the excess oxygen makes it more difficult to ignite the fuel.

[99] Waytulonis, R., Kittleson, D. & Zarling, D., E20 Effects in Small Non-Road SI Engines: A literature and Information Search, 2008, University of Minnesota, Center for Diesel Research: Minneapolis, MN. p. 47.

[100] Environmental Protection Agency. Annual Certification Test Results & Data. 2013 [cited 2013 October 26]; Available from: http://www.epa.gov/otaq/crttst.htm.

[101] Knoll, K. et al., Effects of Intermediate Ethanol Blends on Legacy Vehicles and Small Non-Road Engines, Report 1 - Updated, NREL/TP-540-43543; ORNL/TM-2008-1172009, National Renewable Energy Laboratory. p. 135.

[102] "Drop-in fuels" refers to any biofuels designed to be adequately chemically similar to existing fossil fuel blends that they can be used without adverse consequences.

[103] Hilbert, D., High Ethanol Fuel Endurance: A Study of the Effects of Running Gasoline with 15 percent Ethanol Concentration in Current Production Outboard Four-Stroke Engines and Conventional Two-Stroke Outboard Marine Engines., NREL/SR-5400-529092011, National Renewable Energy Laboratory: Golden, CO. p. 55.

[104] Orbital engine Company, Market Barriers to the Uptake of Biofuels Study: Marine Outboard Driveability Assessment to Determine Impacts of a 10 percent and 20 percent Ethanol Gasoline Fuel Blend on a Small Batch of Engines, Report to Environment Australia2003. p. 40.

[105] The Energy Collective. Replacing Leaded Aviation Gasoline with Renewable Ethanol. 2013 [cited 2013 October 26]; Available from: http://theenergycollective.com/jemillerep/235571/draft-why-doesn-t-epa-replace-leaded-aviation-gasoline-renewable-ethanol.

[106] Bellona. Brazil launches alcohol powered plane. 2005 [cited 2013 October 26]; Available from: http://www.bellona.org/english_import_area/energy/37677.

[107] Ethanol Producer Magazine. Ethanol Takes to the Skies. 2008 [cited 2013 October 26]; Available from: http://www.ethanolproducer.com/articles/4274/ethanol-takes-to-the-skies.

[108] Kass, M. D., Theiss, T., Janke, C. J., Pawel, S. J. & Lewis, S. A., Intermediate Ethanol Blends Infrastructure Materials Compatibility Study: Elastomers, Metals, and Sealants, ORNL/TM-2010/3262011, Oak Ridge National Laboratory: Oak Ridge, TN. p. 109.

[109] This study used a 50:50 blend of isooctane and toluene as the E0 fuel—this mixture is often used in testing because regular gasoline can be variable between samples.

[110] Gilbarco Veeder-Root. 2013 [cited 2013 October 26]; Available from: http://www.gilbarco.com/us/.

[111] It is not clear what proportion of all fuel dispensers used in the United States are newer than five years old or sold by Gilbarco.

[112] Underwriter Laboratories. UL. 2013 [cited 2013 October 26]; Available from: http://www.ul.com/global/eng/pages/.

[113] Gilbarco Veeder-Root. 2013 [cited 2013 October 26]; Available from: http://www.gilbarco.com/us/.

[114] Domestic Fuel. E15 Additions At the Right Price. 2013 [cited 2013 October 26]; Available from: http://domesticfuel.com/2013/09/10/e15-additions-at-the-right-price/.

[115] These are median, not mean, estimates of cost.

[116] Kass, M. D., Theiss, T., Janke, C. J. & Pawel, S. J., Analysis of Underground Storage Tank System Materials to Increased Leak Potential Associated with E15 Fuel, ORNL/TM-2012/1822012, Oak Ridge National Laboratory: Oak Ridge, TN.

[117] Cao, L., Frankel, G. & Sridhar, N., Effect of Oxygen on Ethanol SCC Susceptibility, Part 2: Dissolution-Based Cracking Mechanism. Corrosion, 2013.

[118] U.S. Department of Transportation & Pipeline and Hazardous Materials Safety Administration, Brazilian Biofuel Pipeline Experience, 2008. p. 26.

[119] Cao, L., Frankel, G. & Sridhar, N., Effect of Oxygen on Ethanol SCC Susceptibility, Part 2: Dissolution-Based Cracking Mechanism. Corrosion, 2013.

[120] Whims, J., Pipeline Considerations for Ethanol, 2002, Department of Agricultural Economics, Kansas State University: KS. p. 2.

[121] Ibid.

[122] Association of Oil Pipe Lines & American Petroleum Institute, Ethanol, Biofuels, and Pipeline Transportation, 2010. p. 2.

[123] U.S. Department of Transportation & Pipeline and Hazardous Materials Safety Administration, Brazilian Biofuel Pipeline Experience, 2008. p. 26.

[124] Kinder Morgan. Kinder Morgan: Central Florida Pipeline Ethanol Project. 2009 [cited 2013 October 26]; Available from: http://www.afdc.energy.gov/pdfs/km_cfpl_ethanol_pipeline_fact_sheet.pdf.

125 Lane, J. Kinder Morgan completes ethanol pipeline between New Jersey and New York. 2012 [cited 2013 October 26]; Available from: http://www.biofuelsdigest.com/bdigest/2012/04/04/kinder-morgan-completes-ethanol-pipeline-between-new-jersey-and-new-york/.

126 Department of Energy, Report to Congress: Dedicated Ethanol Pipeline Feasibility Study, Energy Independence and Security Act of 2007, Section 2432010, Department of Energy: Washington, DC. p. 26.

127 The estimated fraction of cars still in use after 12 years (2001–2013) is 0.541 and after 20 years (2022–2001) is 0.079, according to the National Highway Traffic Safety Administration's survivability curve for cars. Since U.S. vehicle sales tend to increase over time, we assume the fraction of cars in the present fleet that were manufactured in 2001 or later is greater than the fraction of 2001 cars that are still driven today.

128 National Highway Traffic Safety Administration, Vehicle Survivability and Travel Mileage Schedules, DOT HS 809 952, National Center for Statistics and Analysis, Editor 2006, NHTSA: Springfield, VA. p. 40.

129 Roberts, R. L., What do we really know about pipeline pigging and cleaning? Pipeline & Gas Journal, 2009. p. 236.

130 Alyeska Pipeline Service Company. Pipeline Facts. 2011 [cited 2013 November 12, 2013]; Available from: http://www.alyeska-pipe.com/TAPS/PipelineFacts.

131 As of 2010, 66 percent of ethanol was transported by rail, 29 percent by truck, 5 percent by barge, and about 1 percent by the Florida pipeline.

132 Department of Energy, Report to Congress: Dedicated Ethanol Pipeline Feasibility Study, Energy Independence and Security Act of 2007, Section 2432010, Department of Energy: Washington, DC. p. 26.

133 Environmental Protection Agency, Regulation of Fuels and Fuel Additives: 2013 Renewable Fuel Standards, Final Rule2013, EPA-HQ-OAR-2012-0546: Federal Register.

134 Department of Energy, Department of Energy Analyses in Support of the EPA Evaluation of Waivers of the Renewable Fuel Standard, 2012, Department of Energy: Washington, DC. p. 9.

135 Tyner, W., Taheripour, F. & Hurt, C., Potential Impacts of a Partial Waiver of the Ethanol Blending Rules, 2012, Purdue University: Lafayette, IN. p. 13.

136 The EPA has responded to limitations in the amount of ethanol that can be supplied in the short term by proposing a reduction in mandated levels of ethanol use in 2014.

137 Environmental Protection Agency, 2014 Standards For The Renewable Fuel Standard Program, EPA-HQ-OAR-2013-04792013, Federal Register: Washington, DC. p. 204.

138 FAO, I., IMF, OECD, UNCTAD, WFP, the World Bank, the WTO, IFPRI and the UN HLTF,, Price Volatility in Food and Agricultural Markets: Policy Responses. Policy Report to the G20 group of nations, 2011.